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GEOLOGY OF THE CERRO DEL MEDIO MOAT RHYOLITE CENTER, VALLES CALDERA, NEW MEXICO

JAMIE N. GARDNER[1], M. MAGDALENA SANDOVAL[2], FRASER GOFF[2], ERIN PHILLIPS[3], AND ARIEL DICKENS[3]
[1]Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, NM 87545
[2]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131
[3]Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801

Abstract — The Cerro del Medio moat rhyolite center is the oldest postresurgence flow and dome complex in Valles caldera. The center consists of five distinctive lava flows and an upheaved dome, amounting to about 5 km^3 of rhyolite. At least two of the effusive phases had associated pyroclastic activity with deposits preserved in the caldera. Additional pyroclastic activity from the Cerro del Medio center can be inferred from pyroclasts in sedimentary deposits in the caldera and fallout and reworked tephras to the east of the caldera. New $^{40}Ar/^{39}Ar$ dates range from 1.229 +/- 0.017 Ma on one of the complex's older flows to about 1.17 Ma on a unit stratigraphically in the middle of the Cerro del Medio sequence. These data indicate volcanism in the Cerro del Medio complex spanned at least 50 to 80 kyr, and other data may imply it spanned more than 100 kyr. Topographic features and sedimentary deposits on the flanks of Cerro del Medio, neighboring moat rhyolite domes, and on the southeastern and southern rim of Valles caldera argue very strongly for an ancient caldera-hosted lake >800 ka with the highest stand at about 2800 m above sea level.

INTRODUCTION

The Cerro del Medio dome and flow complex is the oldest of Valles caldera's postresurgence moat rhyolite centers. Cerro del Medio consists of about 5 km^3 of lava, and sits east of the caldera's resurgent dome, on the northern edge of Valle Grande (Fig. 1). The Cerro del Medio moat rhyolite complex has played important roles through the years, in providing constraints on the timing of resurgent doming in the Valles caldera, being a source of excellent quality obsidian for ancient peoples, being a source of tephras that serve as stratigraphic markers, and playing a role in the plate tectonics revolution. The Cerro del Medio complex is also an aesthetically remarkable place, hosting some of the oldest forests, with trees around 7.5 m in circumference, surviving in Valles Caldera National Preserve, and affording stunning views of many of the valleys that give the caldera its name. We will show that the geology of the complex is far more complicated than acknowledged by previous workers, and that it can provide insights into the possible duration and variety of volcanic activity at a given center in the caldera moat.

PLATE TECTONICS

In the 1960s the theory of plate tectonics, based in large part on concepts of sea-floor spreading (Vine, 1966), was slowly gaining acceptance, but not without considerable controversy. Sea-floor spreading detractors suggested that the magnetic anomaly patterns around midocean ridges had formed by other processes, such as hydrothermal alteration, rather than reversals of the Earth's magnetic field frozen into solidifying basalt. If the anomaly patterns on the sea floor truly were a record of reversals of the Earth's magnetic field, then the same reversals should correlate with reversals recorded in volcanic rocks on land. The moat rhyolite domes of Cerro del Medio, Cerros del Abrigo, and Cerro Santa Rosa in the Valles caldera are where Doell and Dalrymple (1966) recognized the on-land record of one of these reversals. Specifically, they used K-Ar ages and paleomagnetism of these domes to define the Jaramillo normal polarity event, which had been predicted from sea-floor data. The paleomagnetic event was named for Jaramillo Creek, which flows just west of Cerro del Medio. In fact, a popular book that traces the events that led to the plate tectonic revolution was titled *The Road to Jaramillo* (Glen, 1982). Cerro del Medio and the other aforementioned domes have been revisited by additional workers who have since made revisions and refinements to the Earth's geomagnetic time scale (e.g., Izett and Obradovich, 1994; Singer and Brown, 2002).

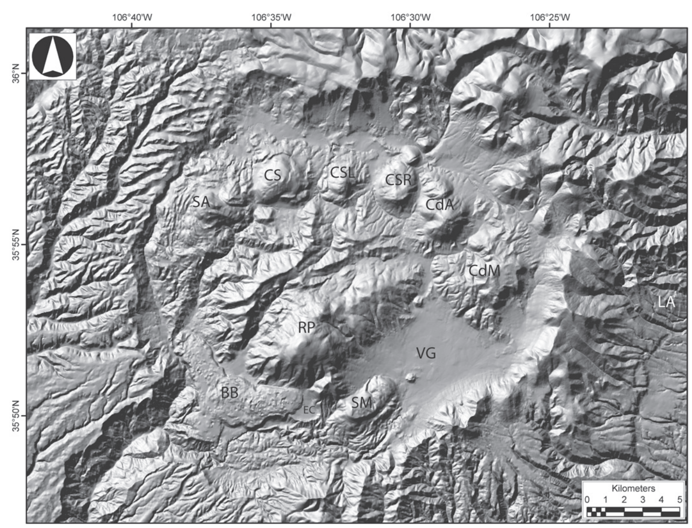

FIGURE 1. Shaded relief map (digital elevation model) of the Valles caldera. VG=Valle Grande. Symbols for moat rhyolites are CdM=Cerro del Medio; CdA=Cerros del Abrigo; CSR=Cerro Santa Rosa; CSL=Cerro San Luis; CS=Cerro Seco; SA=San Antonio Mountain; BB=Banco Bonito; EC=El Cajete; and SM=South Mountain. RP=Redondo Peak on the resurgent dome of Valles caldera. LA=western part of the town of Los Alamos.

VOLCANIC STRATIGRAPHY

Doell et al. (1968) published results of paleomagnetic and K-Ar studies on the rhyolites of Valles caldera, including Cerro del Medio. Significantly, they produced a map that shows a level of detail in the moat volcanic centers not even available in the later geologic map of Smith et al. (1970). Their map divided the Cerro del Medio complex into three flows/domes, designated I, II, III from oldest to youngest. Our work, however, has shown the Cerro del Medio complex to be made up of five distinctive lava flows and one upheaved dome (Fig. 2; Gardner et al., 2006), with deposits from two phases of pyroclastic activity preserved within the caldera. Additional pyroclastic activity from Cerro del Medio is recorded in fallout deposits and reworked tephras east of the caldera on the Pajarito Plateau (e.g. Reneau and MacDonald, 1996; Reneau et al., 2002; Broxton et al., 2006). Stratigraphic relations and dates among the three oldest flow lobes do not permit discrimination of their sequence; thus, they are designated north, west, and south ($Qvdm_n$, $Qvdm_w$, and $Qvdm_s$, respectively). The sequence of eruption of the three youngest phases is clear from field relations, and, thus these units are designated from oldest to youngest $Qvdm_4$, $Qvdm_5$, and $Qvdm_6$. Representative geochemical analyses of each phase are in Table 1.

$Qvdm_6$ is a massive, devitrified, gray, pumiceous rhyolite flow with about 5% small (<2 mm) phenocrysts of sanidine laths and glomerocrysts of sanidine plus opaques. Sanidines are weakly zoned and largely inclusion-free. $Qvdm_6$ erupted through and overlies $Qvdm_5$, and a vent and associated breccia are near the topographically highest point on Cerro del Medio. $Qvdm_6$ activity apparently included explosive phases based on sparsely phyric obsidian pyroclasts with petrographic and geochemical affinities to $Qvdm_6$ that are included in sedimentary deposits that flank the dome complex. Maximum exposed thickness of $Qvdm_6$ lava is about 45 m.

$Qvdm_5$ is an upheaved dome of vitrophyric to devitrified rhyolite about 3 km in diameter. The upheaved dome forms most of the central highlands of the Cerro del Medio complex and its margins near contacts with older units are vertically foliated breccia with elongate clasts, oriented parallel to the contact, set in a very fine-grained matrix. The rocks are locally flow banded, and are sparsely phyric with 1-3% sanidine phenocrysts in blocky and lath-shaped forms. Phenocrysts are moderately zoned and some exhibit cores and zones riddled with glass inclusions. $Qvdm_5$ contains sparse opaque phases and rare clinopyroxene and zircon. Pyroclastic activity was associated with extrusion of this dome, as indicated by a blanket of white to gray, crudely bedded pumice fall deposit with cognate pyroclasts up to 20 cm on the northern flank of the Cerro del Medio complex. Pumice clasts in the fall deposit are petrographically and geochemically similar to the $Qvdm_5$ dome. Thickness of the $Qvdm_5$ fallout deposit is at least 4 m and the thickness of the dome is about 215 m.

$Qvdm_4$ is a massive, brown to black, aphyric obsidian flow that is flow banded and devitrified around its margins. It makes up about half the volume of the entire Cerro del Medio complex. $Qvdm_4$ obsidian is so clean and free of inclusions and phenocrysts that it was a highly desired material for tool and point making by ancient peoples. Ancient quarry sites are abundant on $Qvdm_4$ and lithic scatters include exotic rocks, such as rounded quartzite cobbles from axial river deposits near the Rio Grande, that were used as hammer stones. Ancient peoples quarried $Qvdm_4$ obsidian for so many millennia that there are very few true outcrops left. Obsidian clasts from a pyroclastic flow exposed on the flanks of Cerros del Abrigo show strong geochemical affinities to $Qvdm_4$. Maximum exposed thickness of the $Qvdm_4$ obsidian flow is about 260 m.

$Qvdm_n$ is a gray to light brown, pumiceous, flow-banded, glassy to devitrified rhyolite flow. It is sparsely phyric with about 5% phenocrysts of sanidine, glomerocrysts of sanidine plus opaques, and rare clinopyroxene. Some sanidine phenocrysts are strongly zoned. $Qvdm_n$ occurs as low hills, blanketed with sedimentary deposits, on the north side of the Cerro del Medio complex. It has a maximum exposed thickness of about 30 m.

$Qvdm_w$ is a light brown to black obsidian flow that forms a broad bench on the west side of the Cerro del Medio complex. The obsidian is locally devitrified and flow banded, and is nearly apryric with <1% small (<0.3 mm) sanidine and very sparse magnetite. This obsidian was also quarried by ancient peoples, but is much more poorly exposed than $Qvdm_4$. The bench on top of the flow is covered with sedimentary deposits. $Qvdm_w$ has a maximum exposed thickness of about 120 m.

$Qvdm_s$ is a gray to light brown, flow-banded, sparsely porphyritic, devitrified rhyolite flow that protrudes south from the complex into Valle Grande. It has approximately 5% phenocrysts of sanidine and glomerocrysts of sanidine, sparse hornblende, embayed quartz, and rare plagioclase. $Qvdm_s$ has a maximum exposed thickness of about 75 m.

GEOCHRONOLOGY

The Cerro del Medio complex has presented challenges for radiometric dating from the earliest attempts (Doell et al., 1968). Spell and Harrison (1993) included Cerro del Medio in their $^{40}Ar/^{39}Ar$ study of post-Valles caldera rhyolites in the Jemez volcanic field, but were frustrated with overlapping analytical uncertainties and results that appeared to defy stratigraphy. They used dates from $Qvdm_s$ and $Qvdm_6$ to generate an isochron, yielding a "most reliable age" of about 1.13 Ma for the entire complex. Recent work, however, has shown the age for $Qvdm_s$ to be 1.229 +/- 0.017 Ma (Phillips, 2004; Phillips et al., in press). Izett and Obradovich (1994) published an age for $Qvdm_w$ of 1.207 +/- 0.017 Ma that, although analytically indistinct from Phillips' age for $Qvdm_s$, implies that $Qvdm_w$ is also an older part of the complex. Significantly, three independently determined high precision dates of 1.161 +/- 0.01, 1.169 +/- 0.005, and 1.176 +/- 0.008 Ma (Izett and Obradovich, 1994, Dickens and Phillips, unpubl., and Dickens, unpubl., respectively) have been obtained on $Qvdm_4$. These data indicate that volcanism in the Cerro del Medio complex, from $Qvdm_s$ to $Qvdm_4$, spanned roughly 50 to 80 kyr. Data for $Qvdm_6$ (Spell and Harrison, 1993) are inconclusive, but may imply an additional 50 kyr of volcanism in the Cerro del Medio complex before activity shifted northwest to the

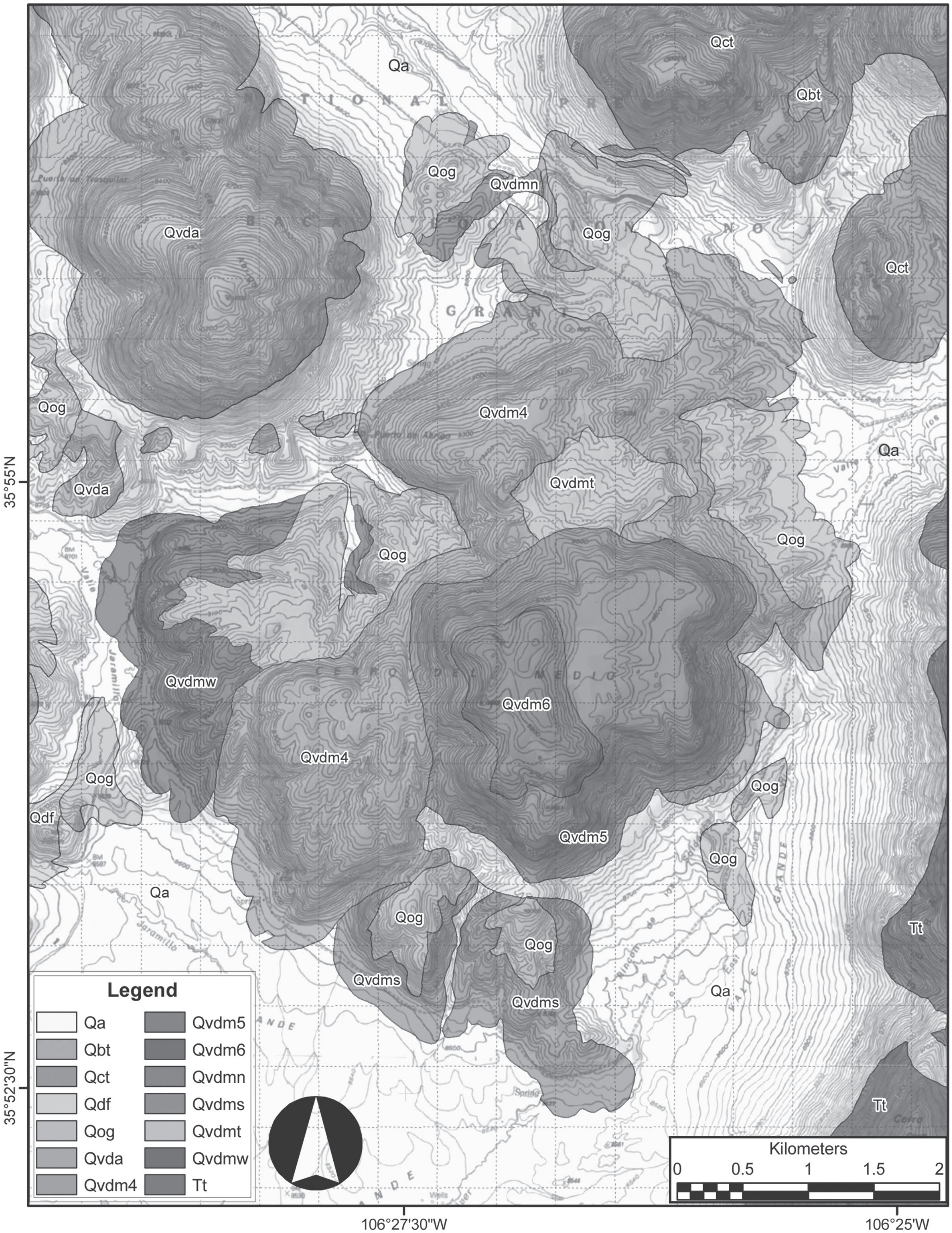

FIGURE 2. Simplified geologic map of Cerro del Medio and surrounding area. Qa=alluvium, fans, landslides, colluvium; Qog=older gravels and sandy gravels; Qvda=undivided rhyolites of Cerros del Abrigo; Qvdm6, Qvdm5, Qvdmt, Qvdm4, Qvdms, Qvdmw, and Qvdmn=units of Cerro del Medio (see text); Qdf=debris flows and caldera-fill on northeast flank of the resurgent dome; Qbt=Bandelier Tuff; Qct=Cerro Toledo Rhyolite, undivided; Tt=Tschicoma Formation (mostly dacites). (Modified from Gardner et al., 2006). For color version of this figure see Plate 15, p. 145.

TABLE 1. Representative geochemical analyses of the Cerro del Medio complex. Unit symbols are the same as in Figure 2. $Qvdm_{pf}$ is obsidian fragments from a pyroclastic flow exposed near the west flank of Cerros del Abrigo. $Qvdm_t$ (shown on Fig. 2) is a pumice fallout deposit associated with eruption of $Qvdm_5$.

	Qvdmn JG02-7	Qvdmw JG02-15	Qvdmw JG02-16	Qvdms JG02-9	Qvdm4 JG02-4	Qvdmpf JG02-6B	Qvdm5 JG03-1	Qvdmt JG02-5	Qvdm6 JG02-1
Normalized Major Elements (Weight %):									
SiO_2	75.69	76.82	76.88	76.96	76.85	76.91	76.51	72.60	75.88
Al_2O_3	13.78	12.91	12.69	12.73	12.66	12.70	12.75	16.94	13.52
TiO_2	0.122	0.091	0.088	0.086	0.091	0.090	0.124	0.182	0.124
FeO*	0.99	0.96	0.95	0.98	0.97	0.96	0.95	1.66	0.98
MnO	0.064	0.049	0.053	0.054	0.054	0.054	0.063	0.058	0.052
CaO	0.38	0.26	0.35	0.24	0.37	0.36	0.05	0.42	0.27
MgO	0.04	0.03	0.04	0.03	0.04	0.04	0.39	0.21	0.05
K_2O	4.83	4.66	4.69	4.71	4.70	4.73	4.38	4.37	4.87
Na_2O	4.10	4.21	4.25	4.19	4.26	4.16	4.78	3.55	4.23
P_2O_5	0.007	0.009	0.006	0.014	0.009	0.007	0.013	0.014	0.016
Trace Elements (ppm) by XRF									
Ni	3	3	2	3	6	1	1	5	3
Cr	0	0	0	0	0	0	1	2	0
Sc	1	3	6	2	1	4	2	9	8
V	0	0	6	2	0	4	0	1	1
Ba	31	28	15	40	26	18	31	48	36
Rb	137	143	153	156	154	153	147	140	137
Sr	8	6	5	8	6	6	4	13	8
Zr	184	155	152	154	153	152	180	182	172
Y	40	27	44	31	43	43	39	37	35
Nb	54.5	52.4	51.0	51.1	52.4	51.4	48.1	61.7	52.7
Ga	21	19	17	21	18	21	20	23	21
Cu	0	0	2	2	1	1	2	1	1
Zn	53	43	52	48	52	54	55	55	45
Pb	29	29	26	46	27	23	27	30	25
La	53	41	43	41	61	46	45	31	63
Ce	101	89	111	93	93	86	85	86	83
Th	14	17	17	16	15	14	16	17	18
Trace Elements (ppm) by ICPMS									
La	44.18	44.56	46.32	44.41	46.64	46.67	45.58	40.75	61.08
Ce	84.06	79.69	86.00	84.67	85.93	86.25	84.10	87.66	80.21
Pr	8.40	7.95	8.83	8.47	8.88	8.90	8.69	7.62	11.88
Nd	29.09	26.60	30.49	28.99	30.72	30.56	30.22	26.75	40.17
Sm	6.65	5.84	7.14	6.64	7.07	7.15	6.89	5.98	8.50
Eu	0.26	0.21	0.20	0.24	0.21	0.22	0.31	0.28	0.47
Gd	6.07	4.99	6.59	5.41	6.46	6.54	6.38	5.30	6.52
Tb	1.09	0.90	1.20	1.00	1.18	1.19	1.14	0.97	1.14
Dy	6.79	5.63	7.47	6.17	7.30	7.40	7.20	6.02	6.61
Ho	1.38	1.10	1.53	1.20	1.49	1.52	1.49	1.22	1.26
Er	3.98	3.08	4.31	3.35	4.24	4.31	4.15	3.47	3.47
Tm	0.61	0.48	0.67	0.51	0.65	0.66	0.64	0.54	0.52
Yb	3.82	3.06	4.24	3.23	4.14	4.26	4.04	3.46	3.25
Lu	0.59	0.46	0.65	0.47	0.64	0.64	0.63	0.52	0.48
Ba	38	35	26	43	27	29	30.00	51	46
Th	17.15	18.11	17.47	17.95	17.01	17.26	17.11	16.84	19.16
Nb	52.74	53.46	51.20	52.58	50.80	51.23	52.40	59.53	52.64
Y	39.42	28.58	42.83	30.53	42.48	42.90	41.98	34.25	33.78
Hf	6.80	6.59	6.31	6.46	6.20	6.25	6.62	6.68	6.68
Ta	3.68	3.84	3.73	3.83	3.67	3.68	3.65	4.11	3.65
U	4.45	4.84	4.82	4.67	4.69	4.79	4.67	3.99	4.29
Pb	27.43	27.94	27.70	44.63	27.53	27.75	26.55	30.62	26.42
Rb	133.1	142.0	149.3	152.7	147.5	149.4	139.50	131.5	134.2
Cs	4.27	4.21	4.89	3.84	4.88	4.88	4.42	5.85	2.53
Sr	5	5	4	6	4	5	6.00	11	7
Sc	2.0	1.8	1.7	1.8	1.8	1.7	2.60	3.1	2.0
Zr	179	158	150	154	150	151	172.00	172	173

Cerros del Abrigo dome center. Thus, volcanism at the Cerro del Medio center in the moat of Valles caldera appears to have lasted more than 100 kyr.

SOME OBSERVATIONS ON OLDER CALDERA LAKES

Numerous workers have recognized evidence that the Valles caldera has hosted lakes (e.g., Sears and Clisby, 1952; Griggs, 1964; Smith et al., 1970), and Gardner and Goff (1996) pointed out evidence for multiple lakes in different parts of the caldera at different times. Indeed, Reneau et al. (this volume) provide excellent and meticulous documentation for three of the caldera's youngest lakes. They additionally point to evidence for older lakes for which the ages and extents are difficult to constrain. We believe that features mapped and described by Goff et al. (2005a, b) and Gardner et al. (2006) are best explained by an ancient caldera lake, likely >800 ka, with a high stand approaching 2800 m elevation. These features include:

1) Prominent benches that appear to be wave-cut on Cerro del Medio, Cerros del Abrigo (973 ka), Cerro San Luis (800 ka), and possibly Cerro Seco (800 ka), between elevations of 2713 and 2800 m (ages from Spell and Harrison, 1993). The most conspicuous of these benches occur at elevations of 2740 to 2774 m.

2) Overlying these benches are deposits of sand and sandy gravels. Gravel lithologies are subrounded subjacent rhyolite and rounded caldera-fill rocks, including distinctive well-rounded cobbles to boulders of densely welded Bandelier Tuff (Unit Qog on flanks of Cerro del Medio and Cerros del Abrigo, Fig. 2).

3) Gravel bars and gravel deposits, and >3 m blocks of Bandelier Tuff that were clearly transported, in notches on the southeast and southern caldera rim at elevations of 2740 to 2800 m.

4) Preservation of primary fallout deposits from Cerro del Medio only at elevations above about 2800 m.

Our explanation for these features is that as the Cerro del Medio and the Cerros del Abrigo domes and flows erupted through the caldera fill, some of these deposits were rafted on the rhyolite carapace. The high-standing lake worked these deposits at its shoreline, cutting the benches and rounding the local rhyolite. Primary fallout deposits on the flanks of Cerro del Medio below the lake stand floated away until the pumice became water-logged and sank into the sedimentary deposits. With outflow from this high-standing lake, gravel deposits were left on the caldera rim.

Reneau et al. (this volume) point out some problematic issues for this high-standing, ancient lake, in particular the western and southwestern portion of the modern topographic rim of the caldera is about 150 m lower than the highest stand (2800 m) of the lake. Curiously, this portion of the modern topographic rim of the caldera is composed of the Bandelier Tuff that erupted during formation of the Valles caldera and the modern elevation is essentially the same as the lowest of the wave-cut benches on the older moat domes. The fact is that we do not know what the western and southwestern parts of the caldera looked like >800 ka because of long-standing erosion and mass wasting through these areas, and burial by younger volcanism. Additionally, active calderas are dynamic places and we do not know how large or how inflated the original resurgent dome was; moreover, we do not know that caldera collapse, particularly on the west, was geologically instant and that portions of the western caldera subsided more gradually over long periods of time. Thus, to us the intriguing question is not that the >800 ka high-standing lake existed, but how it existed. Clearly, this is fruit for future work.

CONCLUSIONS

1) The Cerro del Medio moat rhyolite center consists of five distinctive lava flows and an upheaved dome, comprising about 5 km^3 of lava.
2) In addition to effusion of lavas, at least two eruptions had associated pyroclastic activity with deposits preserved as fallout deposits on the north flank of the center, and a pyroclastic flow near the west flank of Cerros del Abrigo. Additional pyroclastic activity from the Cerro del Medio center can be inferred from pyroclasts in sedimentary deposits in the caldera and fallout and reworked tephras to the east of the caldera.
3) One of the three oldest flow lobes from Cerro del Medio ($Qvdm_s$) has yielded an $^{40}Ar/^{39}Ar$ date of 1.229 +/- 0.017 Ma.
4) Three independently determined high precision dates of 1.161 +/- 0.01, 1.169 +/- 0.005, and 1.176 +/- 0.008 Ma have been obtained on $Qvdm_4$, in the stratigraphic middle of the Cerro del Medio sequence.
5) New dates indicate volcanism in the Cerro del Medio center spanned at least 50 to 80 kyr, and, together with other data, imply volcanism at Cerro del Medio may have spanned over 100 kyr.
6) Topographic features and sedimentary deposits on the flanks of Cerro del Medio, neighboring moat rhyolite domes, and on the southeastern and southern rim of Valles caldera argue very strongly for an ancient caldera-hosted lake >800 ka with the highest stand at about 2800 m above sea level.

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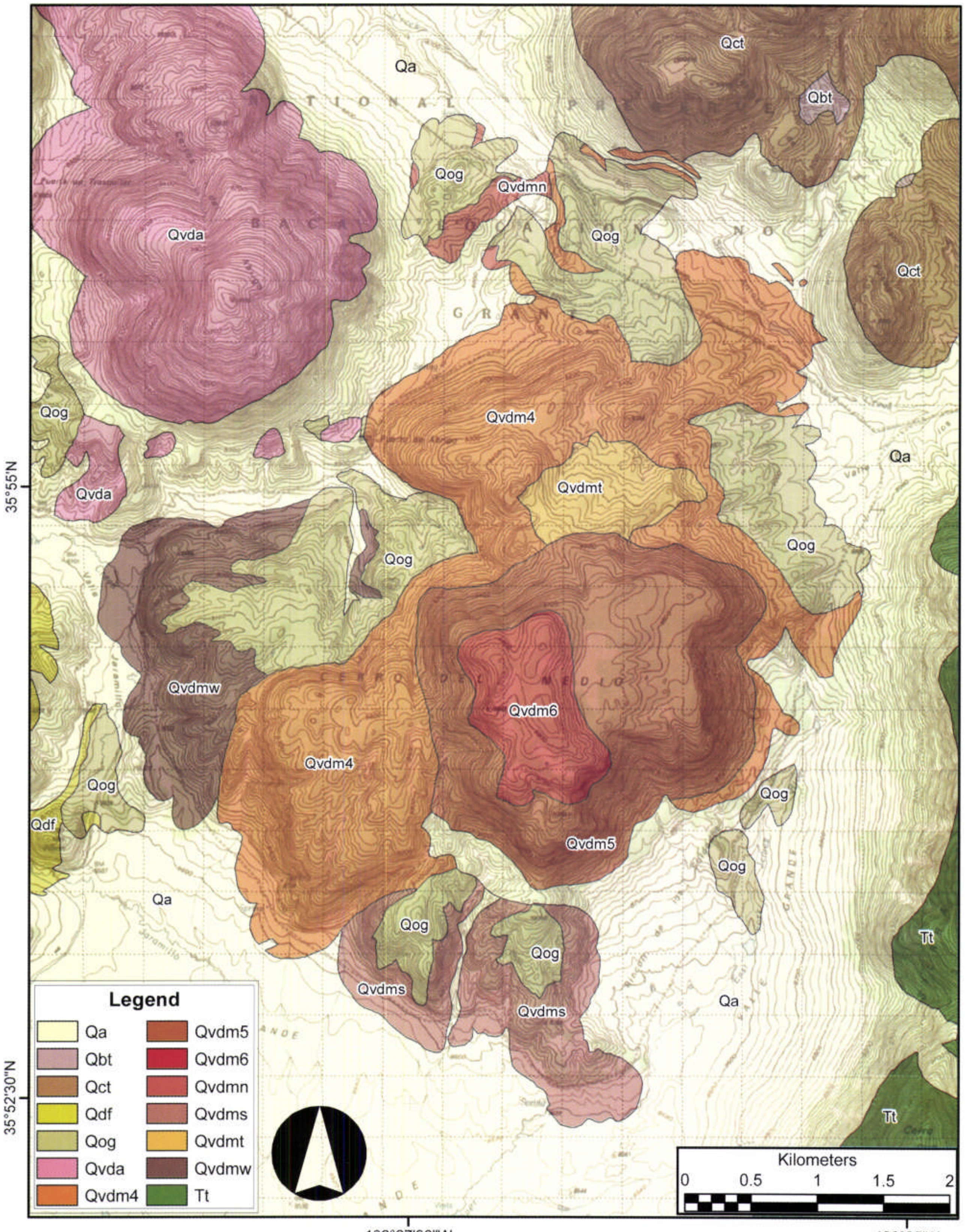

Simplified geologic map of Cerro del Medio and surrounding area. Qa=alluvium, fans, landslides, colluvium; Qog=older gravels and sandy gravels; Qvda=undivided rhyolites of Cerros del Abrigo; Qvdm6, Qvdm5, Qvdmt, Qvdm4, Qvdms, Qvdmw, and Qvdmn=units of Cerro del Medio (see text); Qdf=debris flows and caldera-fill on northeast flank of the resurgent dome; Qbt=Bandelier Tuff; Qct=Cerro Toledo Rhyolite, undivided; Tt=Tschicoma Formation (mostly dacites). (Modified from Gardner et al., 2006). See article by Gardner et al. on page 367.